Soluzioni sostenibili per il settore delle costruzioni: integrazione di materie prime seconde nel ciclo di produzione del calcestruzzo

Sustainable solutions for the construction sector: integration of secondary raw materials in the production cycle of concrete

Soluzioni sostenibili per il settore delle costruzioni: integrazione di materie prime seconde nel ciclo di produzione del calcestruzzo

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ABSTRACT: The construction industry is one of the largest consumers of raw materials and energy and one of the highest contributor to greenhouses gases emissions. In order to become more sustainable it needs to reduce the use of both raw materials and energy, thus limiting its environmental impact. Developing novel technologies to integrate secondary raw materials (i.e. lightweight recycled aggregates and alkali activated "cementless" binders - geopolymers) in the production cycle of concrete is an all-inclusive solution to improve both sustainability and cost-efficiency of construction industry. SUS-CON "SUStainable, Innovative and Energy-Efficiency CONcrete, based on the integration of all-waste materials" is an European project (duration 2012-2015), which aim was the integration of secondary raw materials in the production cycle of concrete, thus resulting in innovative, sustainable and cost-effective building solutions. This paper presents the main outcomes related to the successful scaling-up of SUS-CON concrete solutions in traditional production plants. Two European industrial concrete producers have been involved, to design and produce both pre-cast components (blocks and panels) and ready-mixed concrete. Recycled polyurethane foams and mixed plastics were used as aggregates, PFA (Pulverized Fuel Ash, a by-product of coal fuelled power plants) and GGBS (Ground Granulated Blast furnace Slag, a by-product of iron and steel industries) as binders. Eventually, the installation of SUS-CON concrete solutions on real buildings has been demonstrated, with the construction of three mock-ups located in Europe (Spain, Turkey and Romania) / L'industria delle costruzioni è tra i maggiori consumatori di materie prime ed energia e la maggiore responsabile dell'emissione di gas ad effetto serra. Per diventare più sostenibile essa necessita della riduzione sia nell'uso di materie prime che di energia, così limitando il suo impatto ambientale. Lo sviluppo di nuove tecnologie integranti materie prime seconde (i.e. aggregati leggeri da riciclo e leganti "senza cemento" attivati per via alcalina – geopolimeri) nel ciclo di produzione del calcestruzzo è una soluzione unica per migliorare sostenibilità ed efficienza dei costi nell'industria delle costruzioni. SUS-CON "SUStainable, Innovative and Energy-Efficiency CONcrete, based on the integration of all-waste materials" è un progetto Europeo (durata 2012-2015), il cui scopo è quello di integrare materie prime seconde nel ciclo di produzione del calcestruzzo, così sviluppando soluzioni per costruire innovative, sostenibili e a basso costo. In questo articolo sono riportati i principali risultati relativi allo scaling-up delle soluzioni in calcestruzzo SUS-CON in impianti di produzione tradizionali. Due produttori Europei di calcestruzzo si sono occupati di progettare e produrre sia elementi prefabbricati (blocchi e panelli) che calcestruzzo premiscelato. Come aggregati sono stati utilizzati schiume rigide di poliuretano e plastiche miste, come leganti si sono utilizzati PFA (cenere volante, sottoprodotto di centrali elettriche alimentate a carbone) e GGBS (loppa d'altoforno, sottoprodotto di impianti siderurgici). Infine, le soluzioni in calcestruzzo SUS-CON sono state installate su edifici pilota situati in tre siti Europei (Spagna, Turchia e Romania).

KEYWORDS: *secondary raw materials, sustainable concrete, innovative blocks, innovative panels* / *materie prime seconde, calcestruzzo sostenibile, blocchi innovativi, pannelli innovativi*

1 INTRODUCTION

Concrete is widely used as construction material all over the world. Conventional concrete mainly consists of ordinary Portland cement (OPC) and natural aggregates. OPC production is the second major source of generation of carbon dioxide, after the automobile industry, and its production is highly energy consuming. The use of Alkali-Activated Materials (AAM) from by-products of industrial processes, in place of OPC, is a sustainable alternative for innovative and green construction materials. In addition, the combination of AAMs with recycled aggregates, such as recycled plastics, results in an even more sustainable concrete, contributing to reduce the amount of non-recycled plastic waste sent to landfills. The use of the above mentioned materials in concrete industry has both economic and environmental benefits. On one side it allows the reduction of the cost of cement and concrete manufacturing, on the other hand it has several other benefits such as reduction in landfill cost, energy saving, conservation of natural resources and protecting from environmental problems [1]. In addition, such secondary raw materials represent a serious socio-economic problem to manage and are, at the same time, available in quantity large enough for feeding the concrete industry.

SUS-CON (SUStainable, innovative and energy-efficient CONcrete, based on the integration of all-waste materials) project - funded under the 7th Framework Programme (FP7), call “Materials for new energy efficient building components with reduced embodied energy” - aimed at developing new technology routes to integrate secondary raw materials in the production cycle of concrete, for both ready-mixed and pre-cast applications. The Project, successfully completed in 2015, dealt with the development and industrialization of novel, cost-effective and sustainable concretes based on secondary raw materials such as recycled plastics, used as aggregates, and industrial alumino-silicate by-products (geopolymers), used as binders. The use of plastic aggregates (i.e. heterogeneous plastics, polyurethane foams, exhaust tyres) resulted in lightweight and high thermal insulation concretes, while the use of alternative binders from by-products (i.e. fly ash from power plants, metallurgical slag) had an important impact in terms of CO_2 footprint and embodied energy reduction [2]. The overall scope of the Project included the laboratory research phase and, most importantly, an industrial implementation phase (prototypes development) with the aim to demonstrate the viability of these green alternative materials for the construction industry.

The objectives, challenges as well as some preliminary results of the Project were reported in [3], while the focus of this paper is on the feasibility of scaling up the solutions developed on the laboratory level in real industrial production plants. Panels, blocks and ready-mixed concretes were identified as target products, therefore suitable eco-sustainable geopolymeric concrete formulations were optimized and tested on the lab scale. Two European construction companies were involved as Project partners, Magnetti Building (Italy) and ISTON (Turkey), to validate the feasibility of the developed SUS-CON green solutions in real concrete production plants. The produced prototypes have been tested to assess their mechanical, thermal and fire resistance performances. Three demo sites have been installed in Europe (Spain, Turkey and Romania), using pre-cast components (i.e. panels, blocks) and ready-mix eco-sustainable geopolymeric concretes; the performances in terms of energy efficiency were assessed and compared with similar buildings based on traditional components and materials.

2 DEVELOPMENT OF SUSTAINABLE CONCRETES

2.1 *Materials*

Pulverized Fly Ash (PFA) and Ground Granulated Blasf Furnace Slag (GGBS) were used as alumino-silicate precursors. Physical and chemical properties were assessed [4] to prove their suitability in developing geopolymerization reactions. Commercial chemicals, such as sodium hydroxide (NaOH) and sodium silicate ($Na_2O \cdot nSiO_2 \cdot mH_2O$) solutions, were used to activate the precursors. Rigid Polyurethane (PU) foams and mixed plastics (Remix) scraps were processed by recycling plants to produce lightweight aggregates. More details about the manufacturing processes for the recycled aggregates, physical and chemical properties and their suitability for concretes manufacturing are reported in the relevant literature [5, 6].

Figure 1. Secondary raw materials integrated in SUS-CON concretes: industrial by-products (PFA, GGBS) and post-consumer plastics (mixed plastics and rigid polyurethane foams) / Materie prime seconde utilizzate nei calcestruzzi SUS-CON: sottoprodotti industriali (PFA, GGBS) e plastiche post-consumo (plastica mista e schiume rigide di poliuretano).

Figure 2. SUS-CON binders and aggregates resulted from secondary raw materials / Leganti e aggregati SUS-CON ottenuti da materie prime seconde.

2.2 *Target concrete products*

Panels, blocks and ready-mix concretes were identified as target products for industrial production. At this aim suitable eco-sustainable geopolymeric concrete formulations were optimized and tested at lab scale to get the desired final performance, both in fresh (workability) and hardened state (density and mechanical performance), according to the indications of industrial producers. In **Table 1** the eco-sustainable geopolymeric concretes selected for industrialization are listed together with some relevant properties. A complete characterization in terms of mechanical, thermal and durability behavior can be found in the relevant Project documentation.

SUS-CON concrete	Aggregate	Binder	Density (kg/m^3)
GEO block_P-16	Polyurethane	PFA	942
GEO block_P-21	Polyurethane	PFA/GGBS	1184
GEO block_R-27	Mixed plastic	PFA/GGBS	1475
GEO panel_R-34	Mixed plastic	PFA	1440
GEO panel_P-17	Polyurethane	PFA/GGBS	1040
GEO screed_P-18	Polyurethane	PFA/GGBS	1146

SUS-CON concrete	Compressive strength (MPa)	Flexural strength (MPa)	Thermal conductivity (W/mK)
GEO block_P-16	5.6	1.2	0.16
GEO block_P-21	15.1	2.1	0.21
GEO block_R-27	18.2	2.3	0.27
GEO panel_R-34	6.8	1.3	0.34
GEO panel_P-17	6.4	0.9	0.17
GEO screed_P-18	11.6	1.4	0.18

Table 1. Performance of SUS-CON concretes and relevant applications (adapted from [7]) / Performance dei calcestruzzi SUS-CON e relative applicazioni ([7]).

Products based on PFA/GGBS can be cured at room conditions, while those based only on PFA require a curing in oven at 70°C for 7 days, for this reason these formulations has been used only for pre-cast applications (GEO blocks and GEO panels).

3 INDUSTRIAL PRODUCTION OF INNOVATIVE CONSTRUCTION COMPONENTS

In order to allow the production upscale from laboratory to industrial pilot plants, two European industrial producers, Magnetti Building (Italy) and ISTON (Turkey), were involved. SUS-CON prototypes were designed and produced according the outcomes of the eco-sustainable geopolymeric concretes laboratory optimization. The prototypes were intended both for characterization tests and for demo-buildings construction.

3.1 *Production in Magnetti Building plants (Italy)*

Magnetti Building S.p.A. (Italy), a large company operating in the precast Building and Construction sector, was in charge for design and production of pre-cast prototypes (panels and masonry blocks). The following formulations have been implemented in Magnetti production lines (see **Table 1**): GEO block_P-16, GEO block_P-21 and GEO panel_R-34. In total 15 panels and around 600 lightweight blocks were successfully produced, some allocated to specific characterization tests and others for mock-ups construction (see section 4). The components complied with the specifications for the target applications.

Figure 3. SUS-CON panels production in Magnetti facility / Produzione pannelli SUS-CON presso Magnetti.

Figure 4. SUS-CON blocks production in Magnetti facility / Produzione blocchi SUS-CON presso Magnetti.

SUS-CON elements were produced with the equipment typically used for PC products available in the two productions lines of Magnetti, one dedicated to panels production and the other one to blocks production. Minimum equipment investments were necessary to produce these innovative prefabricated components; such compatibility means good opportunities for the technological transfer of SUS-CON solutions in existing concrete plants.

For a full validation of the produced prototypes, these were tested and compared with traditional elements typically produced in the facility. The characterization included flexural tests on panels, thermal transmittance and fire resistance on blocks and panels as well as thermographic inspections (see Project documentation). Interesting performances resulted from this analysis: the thermal transmittance of SUS-CON blocks was half than traditional blocks (due to their reduced density), while in terms of fire behavior SUS-CON panels were classified as EI 240 (4 times better than reference panels, which are EI 60). These results are very promising in the view of a full-scale industrialization of SUS-CON outcomes.

Figure 5. SUS-CON panels production in ISTON facility / Produzione pannelli SUS-CON presso ISTON.

3.2 *Production in ISTON plants (Turkey)*

ISTON A.S. (Turkey), a large company operating in the Building and Construction sector, was in charge for design and production of pre-cast prototypes (panels and masonry blocks) and ready-mix concrete. The following formulations have been implemented in Iston production line (see **Table 1**): GEO block_P-21, GEO block_R-27, GEO panel_P-17 and GEO screed_P-18. In total 6 panels and around 200 blocks were successfully produced. The components complied with the specifications for the target applications.

It is important to point out that binders from different source were used by ISTON, therefore a preliminary laboratory study was performed to assess their suitability for the final purpose. SUS-CON prototypes were successfully produced also in this case thus demonstrating the high replicability of the results and the adaptability of the developed technologies. Also in this case the industrial producer was able to produce SUS-CON prototypes with minor adjustment of the existing equipment, again confirming that SUS-CON solutions can be easily implemented in existing plants (minimum equipment investments).

Figure 6. SUS-CON blocks production in ISTON facility / Produzione blocchi SUS-CON presso ISTON.

3.3 *Environmental and economic benefits (LCA, LCC), safety issues (HSE)*

Aiming at a wider use of SUS-CON concrete solutions in industrial plants Life Cycle Analysis (LCA), Life Cycle Cost Analysis (LCC) and health, safety and environmental (HSE) studies were carried out.

A previous study [8] has compared SUS-CON solutions with traditional lightweight concretes (based on expanded polystyrene, expanded clay and OPC), assuming Global Warming Potential (GWP, in kg CO_2 eq/m^3) and embodied energy (EE, in MJ/m^3) as indicators. According to this comparative analysis, SUS-CON concretes showed a significant reduction especially in terms of GWP (concretes for panels up to - 64%, for blocks up to - 69% and for screed up to - 73%). Also in terms of EE, SUS-CON solutions can perform better than traditional solutions (up to - 37%, especially when polyurethane aggregates are used). The use of secondary raw materials in concretes avoid also the impacts related to their disposal (landfills or incinerators). Moreover, the use of recycled activators should have a further impact in reduction of both CO_2 emissions and embodied energy.

In terms of costs impacts, SUS-CON solutions were compared with traditional lightweight concretes available on the market (based on expanded polystyrene, expanded clay and OPC). The LCC analysis, referred to the best raw materials prices, has shown that a cost reduction of 15 % for SUS-CON blocks and ready-made screeds can be achieved. If the costs are recalculated considering also activators from secondary raw materials (0 €/kg) also SUS-CON panels resulted in 15% cost reduction. It is evident that there are both economic and environmental benefits in the implementation of SUS-CON concretes in industrial plants. The use of secondary raw materials will definitely reduce concrete products costs and, on the other side, contribute to a significant reduction of the environmental impact of the concrete industry.

As far as regard safety issues, SUS-CON concrete products were tested, according to currently available standards, to ensure their safety for human health and environment. Preliminary HSE tests were performed on the constituent materials, before their use, while final SUS-CON products were evaluated according to specific characterization and leaching tests. SUS-CON aggregates resulted not dangerous according to HSE tests, while for SUS-CON binders, being products already available on the market, no HSE tests was necessary. SUS-CON concretes resulted not dangerous, according to the waste legislation, and, like in the case of traditional concretes, their handling with appropriate protective equipment has no risks.

4 APPLICATION ON REAL SIZE STRUCTURES

In order to demonstrate the actual applicability of SUS-CON solutions on real scale, panels, blocks and screeds produced by Magnetti and ISTON were used for demo buildings located in three different European sites (Spain, Turkey and Romania). Each demo building, with dimensions approximately 2.5x2.5 m, was equipped with door, window and roof. For comparison purpose, similar demonstrators based on reference components were also built. SUS-CON demo buildings, when compared with the reference ones, resulted in better insulation performance.

SUS-CON lightweight components are suitable for non-structural applications where high energy efficiency is required.

Figure 7. Three demo-sites installed in Europe (Spain, Romania and Turkey) using SUS-CON prefabricated components and ready-mixed concretes / Tre edifici pilota installati in Europa (Spagna, Romania e Turchia) realizzati con elementi prefabricate e calcestruzzi pre-miscelati SUS-CON.

5 CONCLUSIONS

In this paper some innovative lightweight concretes, developed within the European project SUS-CON, have been presented. SUS-CON concretes are sustainable materials, consisting in recycled plastic aggregates (rejected polyurethane foams, mixed plastic scraps) combined with green binders (pulverized fly ash from power stations, blast furnace slags from steel plants). SUS-CON concretes were optimized at laboratory scale and, most importantly, fully developed at industrial scale.

SUS-CON lightweight components are suitable for non-structural applications where high energy efficiency is required. Pre-cast components (blocks, panels) and ready-mix concrete were produced in collaboration with two European construction companies (Magnetti Building and ISTON).

The high replicability of SUS-CON processes has been demonstrated using materials from different source and in different plants. The processes are fully compatible with traditional production plants (minimum equipment investments) and not dangerous.

Three demo buildings have been installed in Europe to demonstrate the suitability of the developed products in real conditions. SUS-CON demo buildings, when compared with the reference ones, resulted in better insulation performance. /

Nel presente articolo sono stati presentati alcuni dei calcestruzzi innovativi sviluppati nell'ambito del progetto Europeo SUS-CON. I calcestruzzi SUS-CON sono materiali sostenibili che consistono in aggregati in plastica riciclata (scarti di schiume di poliuretano e di plastica mista) combinati con leganti sostenibili (ceneri volanti da centrali elettriche, loppa d'altoforno da impianti siderurgici). I calcestruzzi SUS-CON sono stati ottimizzati su scala di laboratorio e, cosa più importante, completamente sviluppati su scala industriale.

I componenti alleggeriti SUS-CON sono adatti per applicazioni non strutturali quando sia richiesta alta efficienza energetica. Elementi prefabbricati (blocchi, pannelli) e calcestruzzi pre-miscelati sono stati prodotti in collaborazione con due aziende di costruzioni europee (Magnetti Building e ISTON).

L'alta replicabilità dei processi SUS-CON è stata dimostrata utilizzando materiali di diversa provenienza e diversi impianti. I processi di produzione sono risultati compatibili con impianti di produzione tradizionali (minimi investimenti in attrezzature) e non sono pericolosi.

Tre edifici pilota sono stati installati in Europa così provando l'idoneità dei prodotti sviluppati in condizioni di utilizzo reali. Gli edifici dimostratori SUS-CON, rispetto ad edifici di riferimento, risultano avere migliori proprietà in termini di isolamento termico.

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